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Letter to the Editor

A CO and IRAS study of Cometary Globule 12

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Abstract. Observations of the $J = 2-1$ CO and $C^{18}O$ lines are reported towards the reflection nebula NGC 5367 in the head of Cometary Globule CG 12, which show it to be only the second example known to date of molecular outflow activity in such an object. The CO has a bipolar shape, centred close to the infrared source IRAS 13547-3944. This has a bolometric luminosity ~110 $L_\odot$, and lies close to a 13.5 $M_\odot$ molecular core whose kinetic temperature ~20K and diameter ~0.15 pc. This core appears virialised, and offset from the highest temperature material along the eastern edge of the dense gas - which is probably heated by the UV radiation of a nearby B4 star. A highly collimated (axial ratio $\geq$5) and low-luminosity molecular outflow originates close to this core, extends over a length of 0.9 pc, and contains ~0.05 $M_\odot$ of outflowing material. The structure of the outflow is discussed along with its relationship to the rest of the globule. This is an example of a relatively isolated low-intermediate mass star formation region, which is speculated to have formed as the result of a nearby supernova event 10 - 20 million years ago, and has to date converted about 20 percent of its gas mass into stars.

Key words: Stars: pre-main sequence - Interstellar Medium: jets and outflows

1. Introduction

The reflection nebula NGC 5367 has been proposed as a centre of low-intermediate mass star-formation (Van Till *et al.* 1975) triggered by the expansion of a supernova blast-wave about 10 million years ago. It surrounds the double star h4636 in the head of a prominent Cometary Globule, CG 12 (Hawarden and Brand 1976) and lies at high galactic latitude (b^{II}=21°) in an otherwise unconfused field. NGC 5367 has an opaque optical head with a diameter ~ 10′ , and an elongated tail - seen as wispy filaments of optical absorption and emission, extending ~ 60′ SE of the head. Optical and infrared photometry (Williams *et al.* 1977), showed the likeliest masses of the two stars in the binary system to be 4.5 and 8 $M_\odot$ (i.e. B7 and B4 stars), the latter being surrounded by a dust-shell emitting as a 1600 K blackbody. The most probable distance to NGC 5367 is 630 parsecs, and the mass of the surrounding molecular cloud ~ 120 $M_\odot$. This paper presents CO and IRAS observations of the head of CG 12 close to NGC 5367.

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2. Instrumentation

Observations of the CO and $C^{18}O$ $J = 2-1$ transitions were obtained with the 15 metre James Clerk Maxwell Telescope (JCMT) in July 1992, using cryogenically cooled schottky diode receivers and a digital autocorrelation spectrometer (White 1988). The values of η_{fss} and η_{mb} were 0.8 and 0.6 respectively, and all values reported in this paper have been corrected to T_{mb} , unless otherwise stated. Correcting for sideband gains, the absolute calibration accuracy is estimated to be ± 15 percent, and the pointing was measured to be good to 2″ rms. The CO and $C^{18}O$ maps were sampled on 15″ grids within the shaded areas shown in the greyscale maps of Figures 1 a), b) and within the dotted box in Figure 1 d). The far-IR maps were processed from the IRAS Sky Survey data, using the IPAC *HIRES* algorithm. This uses a Maximum Correlation Method (*MCM*) analysis technique to achieve an approximately four-fold increase in resolution relative to the normal co-add of the IRAS Sky Survey data (Aumann et al 1990). The *MCM* routine was run for 5, 5, 10 and 20 iterations for the 12, 25, 60 and 100 μm bands respectively, to achieve the maximum increase in resolution, while not introducing significant extra noise spikes.

3. The Data

3.1. CO and $C^{18}O$ Observations

Maps of the integrated CO $J = 2-1$ emission and the peak CO temperature are shown in Figure 1. The CO has a butterfly shape, with two lobes separated by ~100″ , lying to the west of the far-infrared point-source IRAS 13546-3947. The CO $J = 2-1$ line intensity reaches T_{mb} = 35K at the centre of the southern lobe, and 26K in the northern one (see Figure 1 b, but is only ~10K at the position of the southern extension seen in the data of Van Till *et al.* (1975), where they find a somewhat higher temperature (exact comparison is difficult since they fail to quote their η_{mb})). There is little velocity structure, the CO $J = 2-1$ lines being relatively narrow (Δv ~2 km s^{-1} at half intensity) almost everywhere (see Section 3.2 later).

The $C^{18}O$ map Figure 1 d) shows a central core ~ 35″ west of the IRAS source, and ~50″ SW of the exciting star h4636 mentioned previously, having a diameter of ~0.15 pc, slightly extended EW. The main beam brightness temperature, T_{mb} , is 5.8 K at the cores centre, and the velocity is constant at -6.3 km s^{-1} everywhere (ie there is no systematic velocity gradient $\geq$ 3 km s^{-1} pc across the core). Assuming an abundance ratio $N(C^{18}O)/N(H_2)$ = 1.8 10^{-7}, the total mass is 13.5 $M_\odot$,

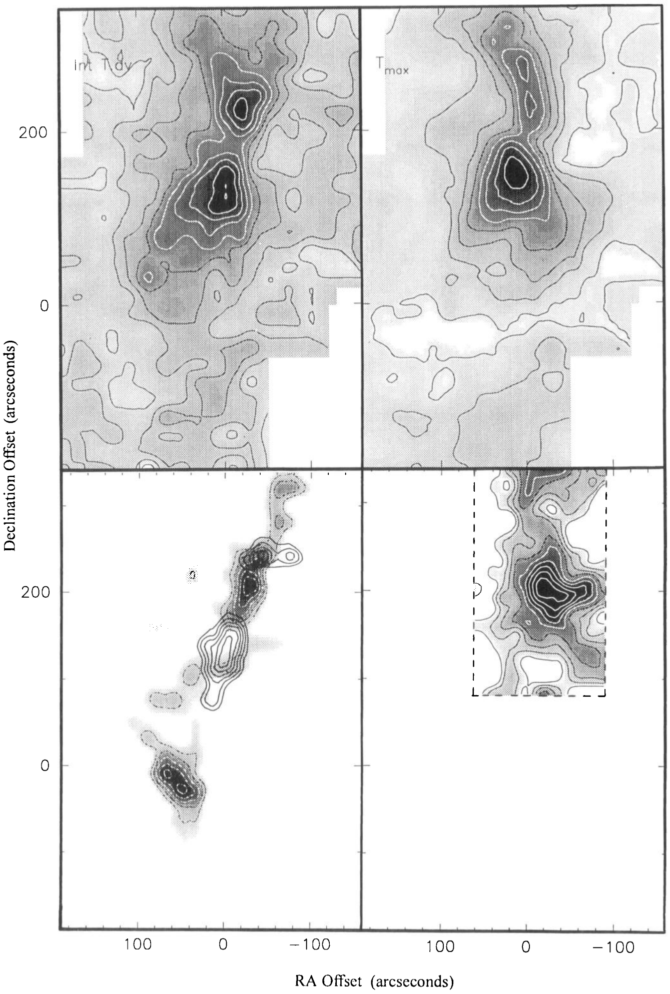

Fig. 1. a) Integrated CO $J = 2-1$ map of NGC 5367. The sampling interval is 15″ and contours are at 5 K steps with the first white contour at 30K km s^{-1} , The central (0,0) position of this and all following maps is $\alpha = 13^h\ 54^m\ 42.0^s$ δ = -39°47′ 42″ . b) Peak CO $J = 2-1$ temperature with contours in 2.5K steps with the first white contour at 17.5K c) high velocity gas integrated for the blue (dashed contours which are overlaid on greyscale and cover -7 to -12 km s^{-1}) and red (solid lines covering -2 to +5 km s^{-1}) wings with contours at 1K intervals starting from 3K km s^{-1} , d) Integrated CO $J = 2-1$ C^{18}O map in 0.5 K km s^{-1} steps, with the lowest contour at 1 K km s^{-1} . The position of IRAS 13547-3944 is indicated by black dot on the maps at the offset position (+7, +215). This lies close to the position of h4636 at (+11, +237) indicated by + symbol. The head of the globule, as seen optically, covers the whole of the mapped region, with the tail extending off beyond the SE corner.

agreeing closely with the virial mass. Assuming the line of sight depth through the core is the same as its diameter, the C^{18}O column density of 2.1 10^{15} cm^{-2} implies a uniform volume density N_{H_2} = 2.2 10^4 cm^{-3} . From the CO spectra towards the centre of the core, the kinematic temperature of the gas, estimated from the peak CO main beam brightness temperature, is $\leq$ 20K. The warmer gas lies along the eastern side of the core, suggesting that the main heating source for the eastern part of the cloud may be the binary system which includes the B4 star in h4636, instead of an embedded object in the C^{18}O core.

3.2. High velocity gas

Although most of the individual CO spectra are narrow (Δv ~2 km s^{-1} at half intensity), and singly peaked, broader lines are seen towards two positions; a) about 2′ south of the map centre, where a broad low level wing extends ~10 km s^{-1} to the redshifted side of the line centre, and b) close to the C^{18}O peak, where the lines are broader and appear self-reversed at -5.2 km s^{-1} . Spectra towards two of the positions showing broad lines are shown in Figure 2.

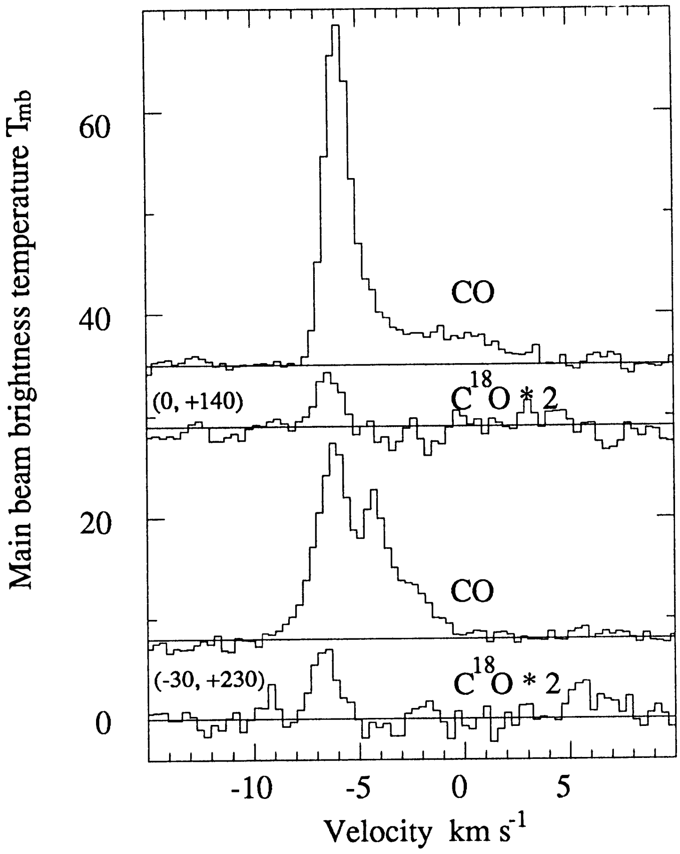

Fig. 2. Spectra in the $J = 2-1$ CO and C^{18}O lines towards the offset positions (0, +140) and (-30, +230). The C^{18}O spectra temperatures have been multiplied by a factor of 2.

Low intensity high velocity gas is seen between -10 and +4 km s^{-1} as shown in Figure 1 c). This high velocity gas forms part of a highly collimated molecular flow (axial ratio $\geq$5) which extends ~5 arc minutes (0.9 pc) along the SE-NW direction. The molecular flow lobes originate at the edge of the C^{18}O core. The flow structure is complex, with red and blue gas co-existing in each of the lobes. The integrated CO $J = 2-1$ emission can be used to estimated the CO column density in outflow material (Bachiller *et al.* 1990). The masses of the blue and red shifted gas are 0.04 and 0.01 M$_\odot$ respectively. The dynamical timescales for both lobes are similar, ~2.7 10^4 years, and the values of the momentum, kinetic energy and mechanical luminosity of the flow are estimated to be 1.6 M$_\odot$ km s^{-1} , 1.7 10^{43} ergs s^{-1} and 4.2 10^{-3} L$_\odot$ respectively (since there is no information on the angle of inclination, i, of the flow to the Earth, it is arbitrarily assumed to be i = 45°). Therefore, this is a relatively low luminosity outflow - comparable to those in other quiescent dark clouds (e.g.Parker *et al.* 1991). It is clearly impossible to be certain that the high velocity gas originated from a single central driving source, particularly because of the complex way that the blue and red-shifted gas overlap. Avery *et al.* (1990) reported similar co-spatiality of red and blue gas for the dark cloud L723, where the possibility of backflow along the outside of the main outflow lobe is discussed, agreeing with modelling by Cabrit *et al.* (1988).

3.3. IRAS observations

The infrared source IRAS 13547-3944 appears in both the IRAS Point Source, and Small Scale Structure catalogues, with total luminosities across the IRAS detector range of ~110 and 250 $L_\odot$ for the point and extended source emission. The point source lies ~ 35″ east of the $C^{18}O$ peak (as mentioned previously in Section 4.1), and is indicated on the HIRES maps shown in Figure 3 a) - d).

The 12 and 25 μm maps show a point-like core, with other compact structures present ~5′ N (at $\alpha = 13^h\ 54^m\ 55.2^s$ δ = -39°41′ 31″) and 10' SE (at $\alpha = 13^h\ 54^m\ 52.8^s$ δ = -39°49′ 37″) of IRAS 13547-3944. These point sources are surrounded by lower brightness emission over an area of size ~1 pc^2. In the longer wavelength bands, the size of the source increases markedly, extending over ~20 x 20′ at 100 μm . These maps show a distribution which generally resembles the large scale CO J=1-0 map of Van Till *et al.* (1975). The southern component (most prominent in the 60 and 100 μm maps) is coincident with the secondary CO $J = 1-0$ hotspot, close to the position of star 2 (a mid-late type B star - Brand *et al.* 1983), which probably heats the nearby cloud edge. Their ^{13}CO map did not however show an enhancement towards this position. Our CO $J = 2-1$ emission has a peak temperature of ~7 K at this point, substantially lower than the $J = 1-0$ values. The infrared luminosity estimated from the IRAS data for this point is ~1.7 $L_\odot$, indicating it not to be substantially heated by an embedded star. It is more likely that the uv radiation of star 2 is heating the edge of the cloud at this point. The dust temperature can be estimated from the ratio of the 60 and 100 μm fluxes. The maps were smoothed using a non-symmetric gaussian smoothing functions, to a 10″ gaussian beam (like to the unsmoothed HIRES processed 100 μm map). The flux ratios (F(100μm) / F(60μm)) at the position of IRAS 13547-3944 and the southern peak of Van Till *et al.* (1975) are 4.2 and 3.2, implying dust temperatures of 32 and 36K respectively, which are similar to the peak main-beam brightness temperatures of the CO $J = 2-1$ data (within calibration uncertainties).

4. Discussion

Two alternative scenarios have been presented to explain the appearance of cometary globules. Reipurth (1983) suggested they were the left over cores of larger clouds, of which the ultraviolet radiation from nearby OB-stars has evaporated the outer parts, leaving behind Bok Globules. The alternative scenario by Brand *et al.* (1983) is for a supernova blast-wave to sweep past a cloud clump, compressing it and causing material to stream out in a tail, giving the characteristic shapes which are seen.

Several other cometary globules have been identified, particularly those related to the Gum Nebula (Pettersson 1992). Associated with this nebula is an unique system of ~ 30 opaque bright rimmed clouds with bright rims, with faint luminous

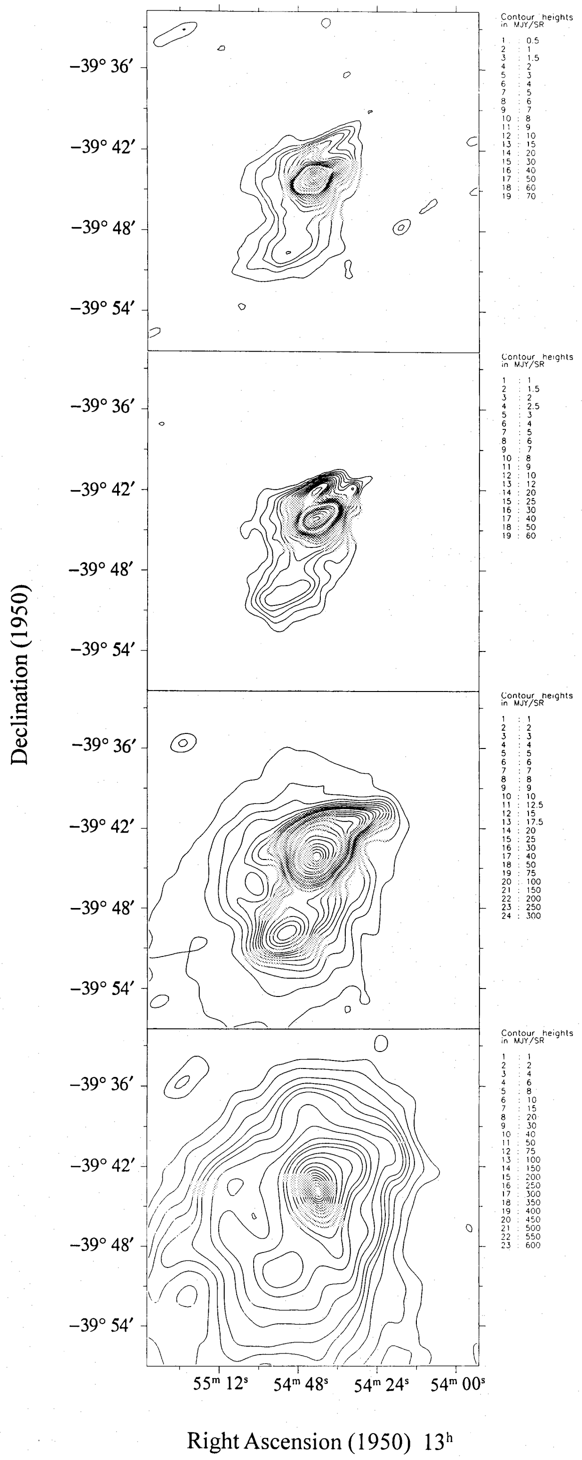

Fig. 3. IRAS maps using the HIRES processing algorithm. The four maps show the a) 12 μm , b) 25 μm , c) 60 μm and d) 100 μm bands respectively, and have beamsizes 78 x 51″ , 120 x 45″ , 96 x 71″ and 101 x 102″ respectively, with the major axes of the distribution at position angle 148°, orthogonal to the in-scan direction. The values of the contours are shown to the upper right of the individual maps (note that the contours are not in equal steps, but are chosen to emphasise the low level emission around the intense central point source). The position of IRAS 13547-3944 is indicated by a black dot.

tails pointing away from the centre of the nebula. CO and infrared surveys have shown several to be active sites of low-mass star formation, leading to speculation that this had been induced by the passage of the blastwave of the fossil supernova shell.

Other objects similar to NGC 5367 are known, including CG 1 (Harju et al 1990) and ESO 210-6A (also known as the HH46-47 system). CG 1 has a mass of $\sim$ 20-45 $M_\odot$, with $\sim$ 75 percent of this in the tail. The gas temperature is $\sim$ 15K, and hydrogen densities $\sim 10^4$ cm^{-3}. There is no evidence for a systematic velocity gradient over the cloud, although shocked gas is seen at some velocities close to the head of the globule. Two $C^{18}O$ clumps are seen in the head, having a total mass of 0.1-0.4 $M_\odot$. Although there is evidence for recent star formation with an efficiency of $\sim$ 10 percent, no molecular outflow was reported at the present epoch. In ESO 210-6A, the total gas mass is $\geq$ 15 $M_\odot$, and the globule shows signs of compression behind its bright rims. A well collimated bipolar molecular outflow is aligned with an optical jet, and extends for $\sim$ 1 parsec. The dynamic timescale, momentum, kinetic energy and mechanical luminosity of this flow are very similar to the values for the NGC 5367 flow.

In the case of CG 12, Williams *et al.* (1977) have speculated that it has been influenced by a high galactic latitude supernova explosion between 10 and 20 Myr ago. The B7 star (star 2) sets a lower limit to the age of CG 12 of $\sim$10 million years, and the detection of the low luminosity molecular outflow surrounding the dense core of CG 12 suggests low mass star formation to be continuing at the present epoch. The relatively high mass in recently formed stars ($\sim$ 20 percent) is significantly higher than seen towards many more quiescent clouds, and supports the notion that a burst of triggered star-formation, which is still working its way through the gas, is forming stars at the present epoch. A systematic mapping programme of Cometary Globules, backed with near and far-infrared studies would be useful to search for further evidence of triggered star-formation in this class of objects. Such a study would also need to consider whether the core is in free-fall collapse, or whether external pressure has driven the collapse, and initiated any current star forming activity.

5. Conclusions

1) The NGC 5367 molecular cloud has kinetic temperatures up to 30K. The absence of strong heating from an embedded source in the cloud core, and the distribution of the warm CO suggests that UV radiation from nearby B stars are strongly heating the cloud edge. Away from the warm gas, the temperature is $\sim$ 10K; typical of quiescent dark clouds.

2) A centrally condensed core with a diameter of $\sim$0.15 parsecs, temperature $\leq$ 20K, and mass 13.5 $M_\odot$ lies $\sim$35$''$ west of IRAS 13547-3944. This core appears to be close to virial equilibrium, but does not contain the dominant heating source for the region.

3) Most of the ambient gas peaks at velocities between 4 and 7 km s^{-1}. No large scale rotation of the cloud or cloud core is seen.

4) A highly collimated, low-luminosity molecular outflow originates close to the core, extending $\sim$0.9 parsecs along the major axis of the cometary globule. The characteristics of this outflow are typical of those found in relatively quiescent low-mass star forming dark clouds.

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